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Power Quality Improvement by RPC for a High Speed Railway Traction System

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ABSTRACT: In electric traction system high speed electric traction power supply involves negative sequence currents problem. In order to improve the power quality and to compensate those negative sequence currents railway power conditioner is presented in this paper. Simulation results were confirmed to achieve good results in terms of lesser negative sequence currents with lesser cost..so that we can say it is a good compensation technique to achieve better performance of high speed electric traction system.

KEYWORDS: Railway power conditioner(RPC), harmonics, current & Voltage compensation, sequence current.

I. INTRODUCTION

Compared with normal electrification railway locomotive load, high-speed locomotive load has some characteristics, such as big instantaneous power, high power factor, low harmonic components and high negative sequence component. A large amount of negative current is injected into grid, which causes serious adverse impact on power system, such as increasing motor vibration and additional loss, reducing output ability of transformers and causing relay protection disoperation..

Recent years, high-voltage, large-capacity Static Var Compensator (SVC), Active Power Filter (APF) and Static Compensator (STATCOM) have become focus on power quality compensation of electrified railway. However, these methods all need high-voltage transformers which increase cost. Reference put forward a proposal of Railway Power Conditioner (RPC), RPC can make comprehensive compensation of negative sequence components, harmonics and reactive power. Reference carries a dual-loop control strategy in order to improve the control effect and performance of RPC. Taken into account the disturbance and variation of electrified railway environment, a recursive proportional-integral control based on fuzzy algorithm is adopted to realize a fast and smooth tracking to reference current. Reference raises a method of setting up two groups of thyristor control reactors (TCR) and two groups of thyristor control 3rd harmonic wave filter besides RPC. The RPC is used to transfer active power; the reactive power is supplied by the TCR and the filter. These works prove that RPC is a effective way to solve the power quality problems in railway system. But the compensator capacity is still too big to make RPC into practice.

This method realizes a minimum compensation capacity which is strictly proved, which reduces 1/3 capacity compared with traditional single station RPC compensation method. The simulation results have verified the correctness of the method proposed in this paper.

II. RAILWAY POWER QUALITY CONDITIONER

A. INTRODUCTION

The AC electrified railway systems have the power quality problems such as the reactive power consumption and the load imbalance due to their inherent electrical characteristics of single-phase and nonlinear moving loads. Also the power electronics equipments in the AC electrified railway systems produce the large amount of harmonic currents. These power quality problems in the AC electrified railway systems have a bad effect on themselves as well as other electric systems connected together. Therefore a power quality compensator is required to maintain the proper power quality in the AC electrified railway systems. An active power quality compensator with two single-phase inverters connected back-to-back (that is called the RPQC in this paper) has been proposed [4. A novel control algorithm based on SRF for the RPQC is proposed. The proposed RPQC control algorithm can properly compensate the harmonic

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currents, the reactive power, and the load imbalance. The effectiveness and the validity of the proposed control algorithm are demonstrated through the simulations.

B. STRUCTURE OF THE RPQC

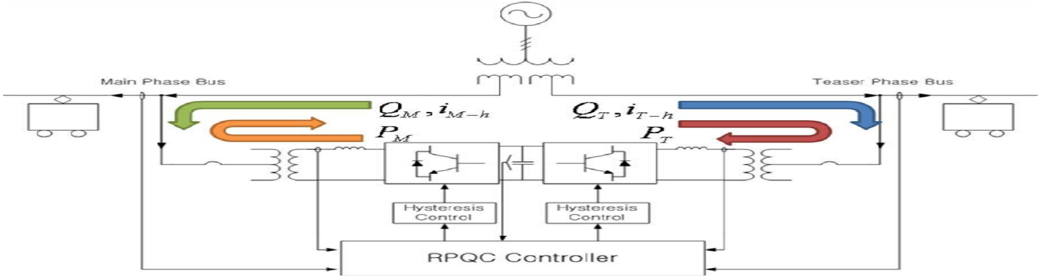


Fig a: Configuration of RPQC

An AC electrified railway system adopting the RPQC. The RPQC consists of two single-phase inverters sharing a DC-link capacitor. Each of the single phase inverters is connected with M-phase and T-phase feeder of the Scott transformer.

The RPQC controller is shown in Fig. b The DC-link voltage for the DC-link voltage regulation, the inverter currents for the current control, and the load currents for the harmonic extraction are required as the controller inputs. The RPQC can compensate not only the harmonic currents and reactive power, but also the load imbalance by exchanging the active power deviation between M-phase and T-phase feeders through the DC-link capacitor. shows an AC electrified railway system adopting the RPQC. The RPQC consists of two single-phase inverters sharing a DC-link capacitor. Each of the single phase inverters is connected with M-phase and T-phase feeder of the Scott transformer. The RPQC controller is shown in Fig. b The DC-link voltage for the DC-link voltage regulation, the inverter currents for the current control, and the load currents for the harmonic extraction are required as the controller inputs. The RPQC can compensate not only the harmonic currents and reactive power, but also the load imbalance by exchanging the active power deviation between M-phase and T-phase feeders through the DC-link capacitor.

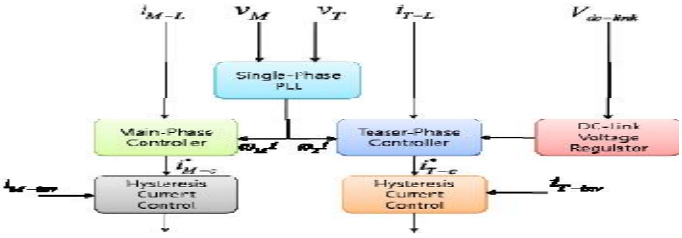


Fig b: RPQC controller.

III. HARMONIC COMPENSATION

The load current of the M-phase feeder that means the current flowing into the locomotives is expressed as follows

$$i_{M-L} = I_{M-L}\cos(\omega t - \phi) \qquad (1)$$

After transforming the load current in equation (1) into the SRF coordinate, the respective d-q components can be expressed as the following equations (2) and (3).

$$I_{M-Ld} = \overline{I}_{M-Ld} + \tilde{I}_{M-Ld} \qquad (2)$$

$$I_{M-Lq} = \overline{I}_{M-Lq} + \tilde{I}_{M-Lq} \qquad (3)$$

where, *M Ld I* − and *M Lq I* − are the DC values of the load current on the SRF. The DC values of the d-q axis are obtained by using the low pass filters. *M Ld I* − % and *M Lq I* − % are the AC values of the load current on the SRF, which means the harmonic contents of the load current. Therefore, when the d-q DC values are subtracted from the d-q load currents, the d-q harmonic currents to be compensated are obtained. Fig. a shows the method to extract the harmonic components from the load current.

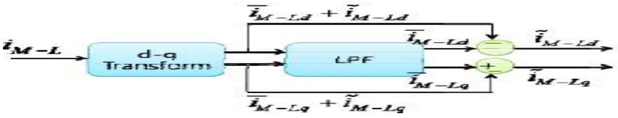


Fig a: Harmonic current extraction

IV. REACTIVE POWER COMPENSATION

The M-phase voltage is represented as follows

$$v_{M-L}=V_{M-L}\cos\omega t \quad (4)$$

Through substituting equations (2) and (3) into equation (1), equation (5) can be derived as follows

$$\begin{aligned} i_{M-L} &= I_{M-Ld}\cos\omega t - I_{M-Lq}\sin\omega t \\ &= I_{M-L}\cos\phi\cos\omega t + I_{M-L}\sin\phi\sin\omega t \end{aligned} \quad (5)$$

Therefore, the single-phase instantaneous active power and reactive power can be described as equations (6) and (7).

$$\begin{aligned} p_M(t) &= v_{M-L}\cdot I_{M-Ld}\cos\omega t \\ &= V_{M-Ld}\cos\omega t\cdot I_{M-Ld}\cos\omega t \\ &= \frac{1}{2}V_{M-Ld}\cdot I_{M-Ld}\,[1+\cos(2\omega t)] \\ &= V_{M-Lrms}\cdot I_{M-Lrms}\cos\phi\,[1+\cos(2\omega t)] \end{aligned} \quad (6)$$

$$\begin{aligned} q_M(t) &= v_{M-L}\cdot I_{M-Lq}\sin\omega t \\ &= -V_{M-Ld}\cos\omega t\cdot I_{M-Lq}\sin\omega t \\ &= -\frac{1}{2}V_{M-Ld}\cdot I_{M-Lq}\sin(2\omega t) \\ &= V_{M-Lrms}\cdot I_{M-Lrms}\sin\phi\sin(2\omega t) \end{aligned} \quad (7)$$

where, V_{M-Lrms} and I_{M-Lrms} denote the RMS value of v_{M-L} and v_{M-L}, respectively. It is shown that the single phase instantaneous active power depends on the d-axis current value, while the instantaneous reactive power depends on the q-axis current value. The source current, i_{M-s} is made by the load current of M-phase, i_{M-L} and the inverter current, i_{M-inv}, as in equation (8)

$$i_{M-s}=i_{M-inv}+i_{M-L} \quad (8)$$

If the q-axis value of the source current becomes zero through the compensation of the q-axis current, the corresponding reactive power can be compensated. Fig. b shows the control blocks of reactive power compensation algorithm.`

Fig b: Reactive power compensation algorithm.

V. LOAD IMBALANCE COMPENSATION

It is shown in equation (6) that the single-phase instantaneous active power can be properly controlled by controlling the d-axis current. If the harmonic currents and the reactive power have been compensated by the proposed compensation algorithm, the load imbalance is provoked by a deviation between the active power load of the M-phase and that of the T-phase. For example, the load current of the M-phase is larger than the T-phase when the load of the

Mphase is larger than T-phase, then the load imbalance problem is occurred. This results into that the d-axis current of the M-phase is larger than that of the T-phase. The d-axis values of the M-phase and the T-phase are equal to each other when three-phase balancing condition is considered. This load imbalance compensation can be achieved if the difference between the d-axis source currents of the Mphase and the T-phase is controlled to be zero. Fig. 5 shows the control blocks of load imbalance compensation algorithm.

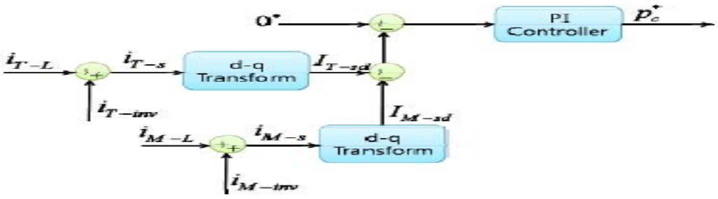


Fig a: Load imbalance compensation algorithm.

VI. OVERALL RPQC CONTROLLER

Fig. a shows the structure of overall RPQC control scheme. M-phase controller and T-phase controller are fundamentally on the same structure together. However, in this paper, the T-phase controller involves the DC-link voltage regulation loop, and the sign of load imbalance compensation loop of the M-phase and the T-phase controller is opposite because the reference direction of power flow is on the T-phase. The DC-link voltage regulation and the load imbalance compensation are achieved on the d-axis and the reactive power compensation is performed on the q-axis. The harmonic currents compensation is performed on both of the d-q axis. Hysteresis current control is employed for the inverter current control.

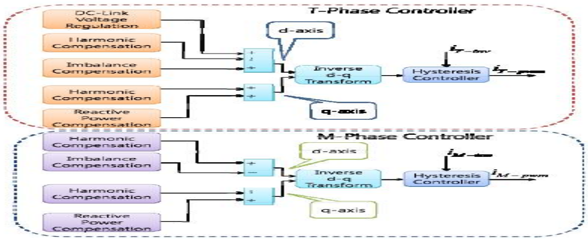


Fig a: Control block diagram of overall RPQC controller.

VII. PULSE WIDTH MODULATION CONTROL

The advantages of the PWM control scheme are:

a) The output voltage control can be obtained without addition of any external components.
b) PWM minimizes the lower order harmonics, while the higher order harmonics can be eliminated using a filter.

The disadvantage possessed by this scheme is that the switching devices used in the inverter are expensive as they must possess low turn on and turn off times, nevertheless PWM operated are very popular in all industrial equipments. PWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. There are different PWM techniques which essentially differ in the harmonic content of their respective output voltages, thus the choice of a particular PWM technique depends on the permissible harmonic content in the inverter output voltage.

A. SINUSOIDAL-PULSE WIDTH MODULATION (SPWM)

The sinusoidal PWM (SPWM) method also known as the triangulation, sub harmonic, or sub oscillation method, is very popular in industrial applications and is extensively reviewed in the literature [1-2]. The SPWM is explained with reference to Figure a, which is the half-bridge circuit topology for a single-phase inverter.

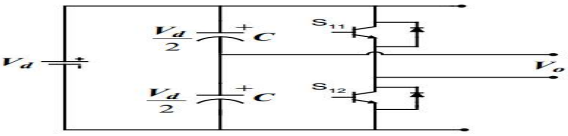
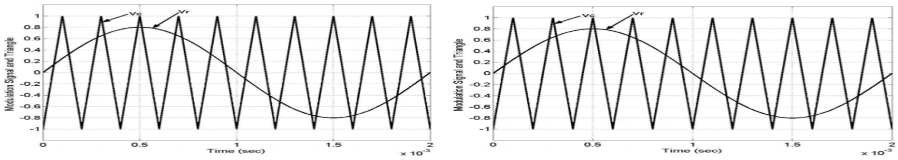


Fig a: Schematic diagram for Half-Bridge PWM inverter.

For realizing SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference of the desired frequency. The intersection of and waves determines the switching instants and commutation of the modulated pulse. The PWM scheme is illustrated in Figure a, in which v is the peak value of triangular carrier wave and v that of the reference, or modulating signal. The figure shows the triangle and modulation signal with some arbitrary frequency and magnitude. When sinusoidal wave has magnitude higher than the triangular wave the comparator output is high, otherwise it is low.

$$v_r > v_c \qquad S_{11} \text{ is on }, \quad V_{out} = \frac{V_d}{2}$$

$$v_r < v_c \qquad S_{12} \text{ is on }, \quad V_{out} = -\frac{V_d}{2}$$



(a) (b)

Fig: SPWM illustration (a) Sine-Triangle Comparison (b) Switching Pulses after comparison.

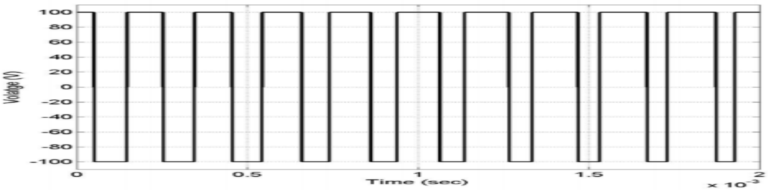
The comparator output is processes in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. The magnitude ratio of v_r/v_c is called the modulation index (m_i) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to m_i. The amplitude v_c of the triangular wave is generally kept constant. The frequency–modulation ratio m_f is defined as

$$m_f = \frac{f_t}{f_m} \qquad (2.3)$$

To satisfy the Kirchoff's Voltage law (KVL) constraint, the switches on the same leg are not turned on at the same time, which gives the condition

$$S_{11} + S_{12} = 1 \quad (2.4)$$

for each leg of the inverter. This enables the output voltage to fluctuate between $V_d/2$ and $-V_d/2$as shown in Figure 2.4 for a dc voltage of 200 V.



Figc: Output voltage of the Half-Bridge inverter.

VIII. MODELLING OF CASE STUDY

A. RPC STRUCTURE AND ANALYSIS OF COMPENSATION PRINCIPLE

The structure of RPC is shown in Fig.a. Three phase 220kV voltage is stepped down into two single-phase power supply voltage at the rank of 27.5kV by V/V transformer. RPC is made of back-to-back voltage source converters and a common dc capacitor, which can provide stable dc-link voltage. Two converters are connected to secondary arms of V/V transformer by step down transformer. Two converters can transfer active power from one power supply arm to another, supply reactive power and suppressing harmonic currents.

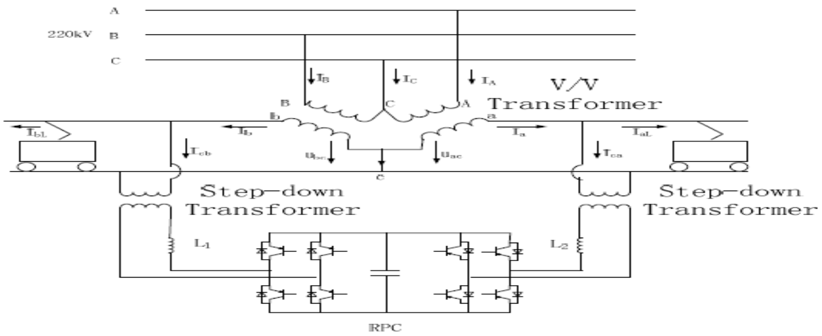


Fig a: Traction power system with a three-phase V/V transformer and a RPC

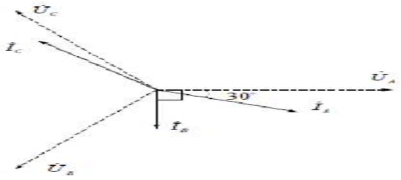
The right feeder section in Fig.a is denoted as *a*-phase power arm, while that the left side is *b*-phase power arm. The corresponding phases on the primary side are denoted as Phase A and Phase B, respectively. Since using four-quadrant pulse rectifiers to feed electrical locomotives, the power factor of high speed electrical locomotive is close to 1. Set U_A as the reference value. Assume that the fundamental current vector of *a*-phase power arm is $\dot{I}_{aL}$ and the fundamental current vector of *b*-phase power arm is $\dot{I}_{bL}$. $\dot{I}_{aL}$ and $\dot{I}_{bL}$ are shown as follows :

$$\begin{cases} \dot{I}_{aL} = I_{aL} e^{-j30^\circ} \\ \dot{I}_{bL} = I_{bL} e^{\ j90^\circ} \end{cases} \tag{1}$$

The turns ratio of V/V transformer is *K*, so the three currents of the high-voltage side are shown as follows:

$$\dot{I}_A = \frac{\dot{I}_{aL}}{K} = \frac{I_{aL}}{K} e^{-j30^\circ} \quad , \quad \dot{I}_B = \frac{\dot{I}_{bL}}{K} = \frac{I_{bL}}{K} e^{-j90^\circ} \quad , \quad \dot{I}_C = -(\dot{I}_A + \dot{I}_B) \tag{2}$$

Before RPC compensation, *a*-phase power arm has load current $\dot{I}_{aL}$ and the *b*-phase power arm has load current $\dot{I}_{bL}$. Assume that $\dot{I}_{aL} > \dot{I}_{bL}$, the three phase current is shown in Fig.2

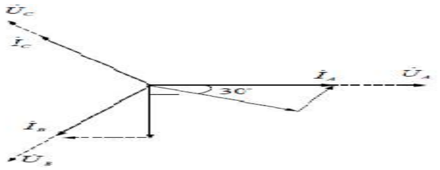


Figb: Three-phase current phase diagram without compensation

It is obvious that three phase current is unbalance before compensation. Use RPC to shift $\frac{1}{2}(I_{aL} - I_{bL})$ from *a*-phase to *b*-phase. Then, the current of two power arms are compensated to $\dot{I}'_{aL}$ and $\dot{I}'_{bL}$, and they have an equal amplitude of $\frac{1}{2}(I_{aL} + I_{bL})$ and an angle difference of $\pi/3$. The unbalance level is 50% now.

On the basis of active power transfer, RPC should compensate a certain quantity of capacitive reactive current I_{caq} on the power arm a and a certain quantity of inductive reactive current I_{cbq} on the power arm b, which can make the current of a-phase power arm lead the corresponding voltage π /6 . At this point, the reactive current should be calculated as follows:

$$I_{caq} = I_{cbq} = \frac{1}{2}(I_{aL} + I_{bL})\tan 30^\circ \qquad (3)$$



Figc: Three-phase current phase diagram after adjusting active and reactive power by RPC

After the compensation, the currents I_A and I_B have the same amplitude, as shown in Fig.3, and their angle difference is $2\pi/3$. The C phase current IC can be obtained as $I_C = -I_A - I_B$. The primary side of traction transformer has a balance three-phase current after active power shift and reactive power compensation. It is similar when $I_{aL} < I_{bL}$. The common expression of RPC compensation current is:

$$\dot{I}_{ca} = \frac{1}{2}(I_{bL} - I_{aL})e^{-j30^\circ} + \frac{1}{2\sqrt{3}}(I_{aL} + I_{bL})e^{j60^\circ} \quad \dot{I}_{cb} = \frac{1}{2}(I_{aL} - I_{bL})e^{-j90^\circ} + \frac{1}{2\sqrt{3}}(I_{aL} + I_{bL})e^{j180^\circ} \qquad (4)$$

$\dot{I}_{ca}$, $\dot{I}_{cb}$ --the equivalent current of RPC converters of *a*-phase arm and *b*-phase arm at the voltage of 27.5 kV.

B. PRINCIPLE OF COLLABORATION COMPENSATION

Since phase sequence rotation is widely adopted in traction power supply system, 3 stations collaboration compensation is mainly discussed in this paper. The structure of 3 stations collaboration compensation is shown in Fig.a.

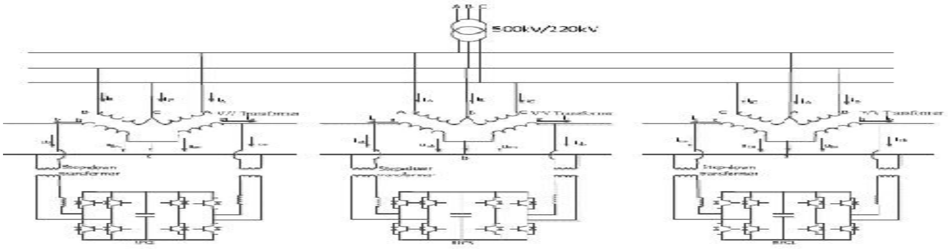


Fig a: Schematic diagram of collaboration compensation of three stations

The capacity in phase CA, AB and BC is x,y,z , which has a relationship of $x>y>z$. The network of x,y,z can be divided into two parts, the one is a balanced network of z,z,z , the other is an unbalanced network of x-z, y-z, 0. Assume that $X = x - z$,$Y = y - z$, the original network is simplified as $X,Y,0$. Set $X/2$ as the reference value, the p.u. value of the simplified network is 2,Y' ,0. Y' is varying from 0 to 2. The extreme case is Y' =0. The optimize compensation strategy is shown below:

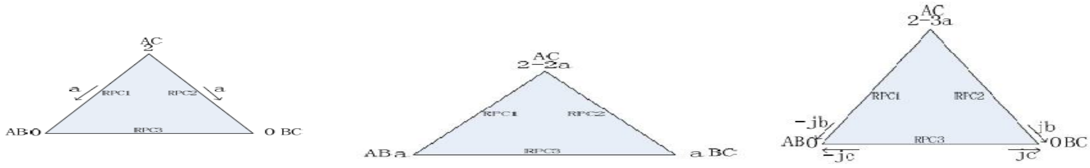
B.i). Single RPC compensation:

Based on the compensation strategy of RPC, when there is a maximum capacity in one of the traction feeder arms, RPC transfers $\frac{1}{2} * \frac{X}{2}$ active power from one traction feeder arm to another. And then compensates$\frac{1}{2\sqrt{3}} * \frac{X}{2}$ reactive power to both traction feeder arms based on Steinmetz theory. So the compensation capacity of single RPC is:

$$S = \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2\sqrt{3}}\right)^2}\ \frac{X}{2} = 0.2885X \qquad (5)$$

B.ii) Three stations collaboration compensation:

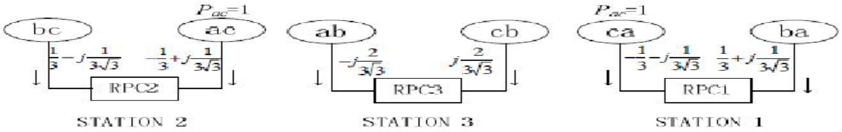
The simple model of 3 stations structure is shown in Fig.5. Since RPC could transfer a quantity of active power and compensate reactive power, a triangle is applied to illustrate the principle of collaboration compensation: apexes of the triangle are regarded as active load in Phase-AC, Phase-BC and Phase- AB, and edges of the triangle are regarded as three railway power conditioners. There are three steps to compensate. Firstly, transfer a quantity of active power. Secondly, separate the network into two parts: a balanced network and an unbalanced network. And last, make compensation to the unbalanced network based on the Steinmetz theory.



(a)Active power delivery (b)Three phase power after active power delivery (c) Reactive power compensation based on Steinmetz theory

According to the Steinmetz theory, fully compensation should satisfy the relationship of $b+c \geq \frac{2-3a}{\sqrt{3}}$.The capacity of three RPC is $\sqrt{a^2+b^2}$, $\sqrt{a^2+b^2}$, c separately. The installed capacity will be the maximum of the three RPC capacities above. So we can obtain the minimum installed capacity when $\sqrt{a^2+b^2}=c$. The results can be conducted a=$\frac{1}{3}$, b = $\frac{1}{3\sqrt{3}}$ and the minimum capacity is $S_{\min}=\sqrt{a^2+b^2}=c=\frac{2}{3\sqrt{3}}$ This is a fully compensation but the station where RPC2 installed is capacitive. To avoid this condition, RPC1 supply inductive reactive power with the value of *b*, and RPC2 supply capacitive reactive power with the value of *b*, too. So the capacitive condition is avoided and the system keeps balance at the same time.

Working condition of three stations is shown in Fig.6. The ellipses stand for different traction feeder arms, the squares stand for RPC which connect to traction feeder arms. The arrows stand for active power transfer and reactive power compensation.



d)Working condition of three stations which supply active power and reactive power

Three stations collaboration compensation minimum capacity is:

$$S_3=\sqrt{\left(\frac{1}{3}\right)^2+\left(\frac{1}{3\sqrt{3}}\right)^2}\,\frac{X}{2}=\frac{2}{3\sqrt{3}}*\frac{X}{2}=0.1925X \qquad (3)$$

Which is 2/3 of the capacity of single RPC compensation. Tab.1 shows the compensation capacity of the two strategies.

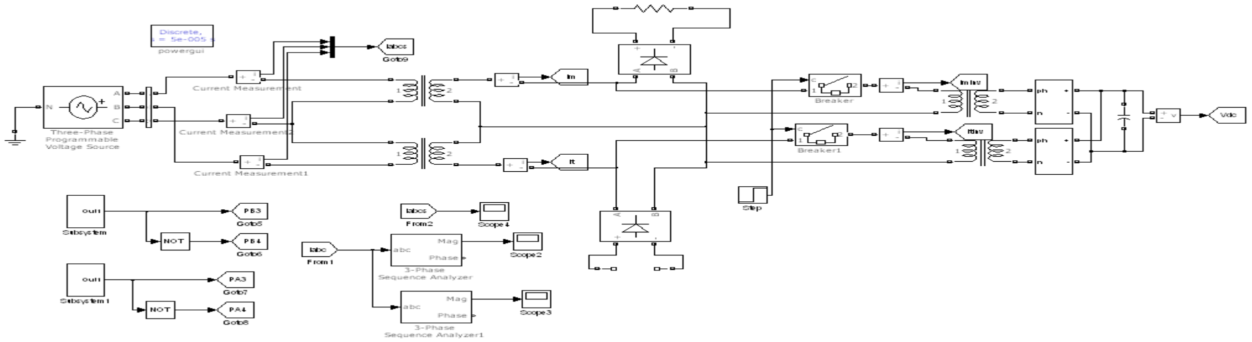
Compensation mode	Single station	Three station collaboration compensation
RPC capacity	$0.2885X$	$0.1925X$

Table 1comparision of two compensation method

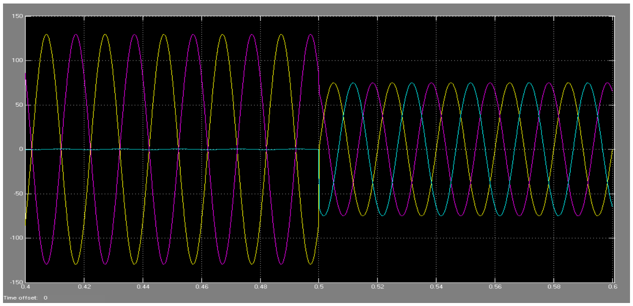
It can be proved that this installed capacity (0.1925*X*) can satisfy any condition when *Y'* varying from 0 toIf there is *N* stations connect to one 220kV bus, *N* may be 3*n*, 3*n*+1 or 3*n*+2 (*n*=0,1,2…). When *N*=3*n*, it means there are n sets of 3-stations compensation. When *N*=3*n*+1, it means there are n sets of 3-stations compensation and a single station compensation. When *N*=3*n*+2, it means there are *n* sets of 3- stations compensation and 2 single station compensation

IX. SIMULATION RESULTS

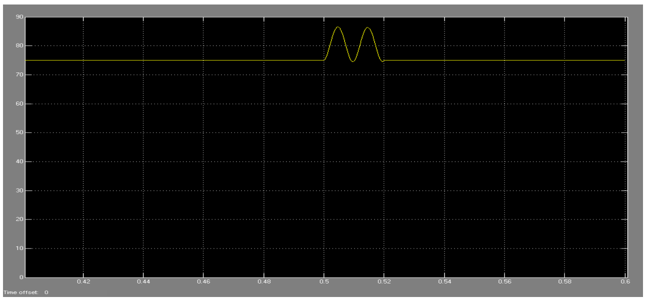
SINGLE STATION COMPENSATION



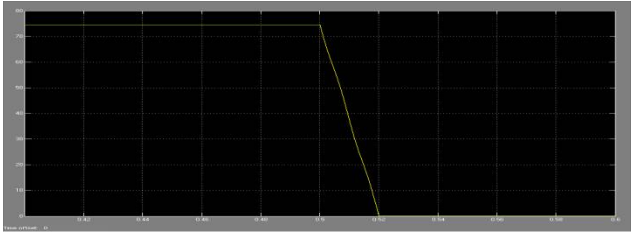
CURRENT OF TRACTIVE TRANSFORMER HIGH VOLTAGE



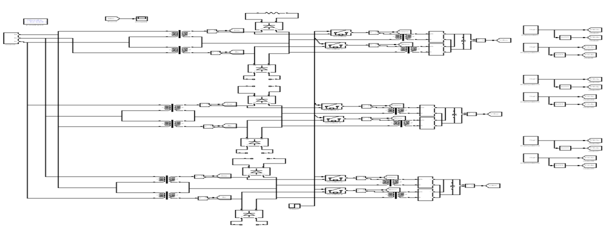
POSITIVE SEQUENCE CURRENT



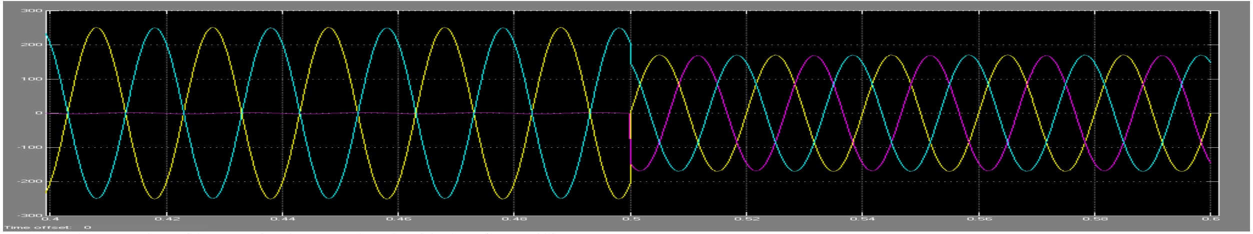
NEGATIVE SEQUENCE CURRENT



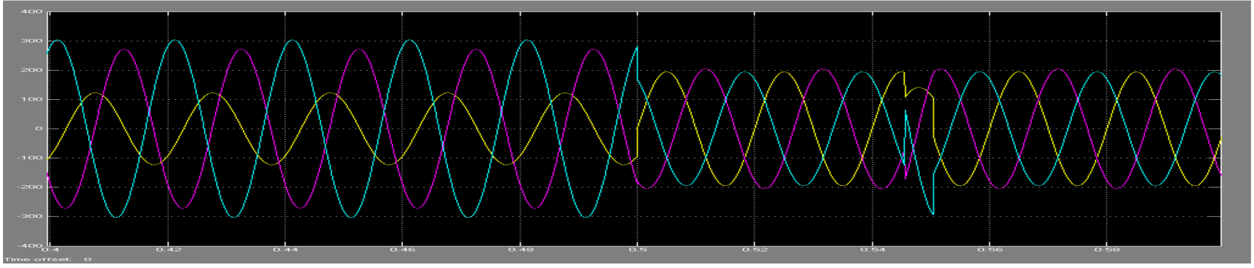
THREE STATION COLLABORATION COMPENSATION

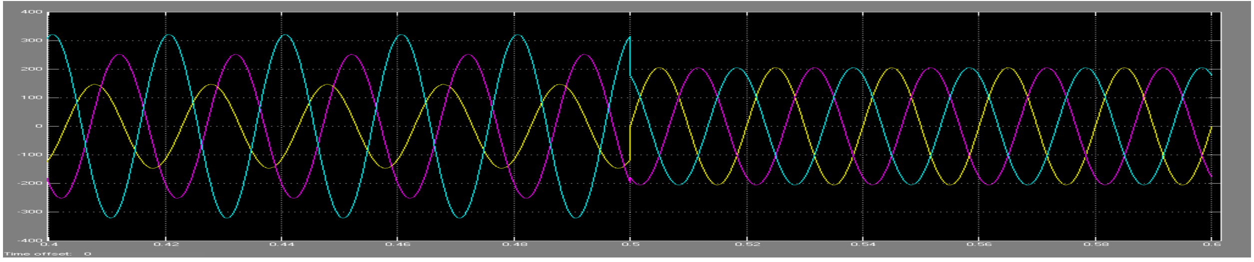


CURRENT OF TRACTIVE TRANSFORMER HIGH VOLTAGE SIDE (Y=0)



CURRENT OF TRACTIVE TRANFORMER HIGH VOLTAGE SIDE (0<=Y<=2/3)




CURRENT OF TRACTIVE TRANSFORMER HIGH VOLTAGE SIDE(2/3<=Y<=1)

X.CONCLUSION

This project proposes a new power quality compensation system which is composed of several railway power conditioners. The proposed system can be used to compensate negative sequence current in high speed electrified railway. A minimum installed capacity is conducted which is 2/3 of the traditional single station compensation capacity. A new compensation strategy is raised Simulation results show that the proposed collaboration compensation of railway power conditioners is effective. It can reduce compensation capacity and has a good performance at negative sequence current compensation.

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